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JET PROPULSION LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

PASADENA, CALIFORNIA

June 1, 1962

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I. INTRODUCTION

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The studies summarized in this Report were conducted to determine whether or not there is adequate justification for seriously considering the propelled capsule approach for the Mariner B spacecraft (Ref. 1). The studies were a joint effort by representatives of Divisions 31, 34, 35, and 38 of the Laboratory, and were conducted utilizing specific trajectory data for the 1964 Mars opportunity only because these data were currently available. Although the approach geometry will be somewhat different for the 1966 and later opportunities, it is an[illegible]pated that these differences will not affect the conclusions reached in this investigation.

The advantages of propelling the capsule from the spacecraft on a fly-by trajectory, as opposed to merely dropping it from the spacecraft on an impact trajectory and then diverting the spacecraft bus (discussed in Ref. 2), are briefly summarized below:

1. Enhancement of over-all mission reliability by minimizing the number of spacecraft propulsion maneuvers
2. Elimination of spacecraft bus sterilization by substantially reducing the probability of impact on the planet
3. Over-all weight saving by trading the miss-maneuver on the heavy bus for an impact maneuver with the lighter capsule, and also eliminating the need for a very accurate approach trajectory for the spacecraft
4. Elimination of the spacecraft-capsule eclipse by Mars after capsule entry.

AUTHOR

II. SYSTEMS SELECTED FOR STUDY

The two systems selected for detailed investigation were: (1) the passive capsule system (nonpropelled), described in Ref. 3, and (2) the propelled capsule system. For both configurations, the representative systems selected for study were those presenting the least risk to the fly-by mission.

A. Passive Capsule System

Since the passive capsule system was discussed thoroughly in the Mariner B Study Report (Ref. 3), only a brief description will be presented here. The basic sequence of events is as follows:

1. The midcourse correction(s) will aim the spacecraft on an impact trajectory towards the capsule aim point on Mars.
2. Dispersions in the impact trajectory will be reduced to approximately ±800 km (2.5 σ) at Mars by making two approach corrections at distances of approximately 1,500,000 km and 400,000 km from Mars.
3. After the second approach correction, the capsule will be separated from the spacecraft by a small (spring) impulse.
4. Upon completion of the capsule launch, the spacecraft bus will be reoriented and the miss-maneuver will be performed by the midcourse propulsion system.
5. The capsule will enter the Martian atmosphere and land, and the bus will fly by the planet. The dispersion of the fly-by trajectory from the intended aim point will be approximately

±800 km (2.5 σ). After the capsule lands, the spacecraft bus may be eclipsed. The eclipse duration will vary up to 2.4 hours, depending on the dispersion.

The midcourse correction, the two approach corrections, and deflection maneuvers are to be performed by the midcourse propulsion system. If the midcourse propulsion system or the spacecraft orientation system fails, then the spacecraft will have a high probability of impacting the planet, as shown in Table 1.

Table 1. Approach trajectory dispersions for passive capsule (for aim point, see Fig. 1)

Maneuver failure	Probability of fly-by trajectory being successful (within Region I of Fig. 1) percent	Probability of impact percent
First approach correction	1.7	56
Second approach correction	0.06	81
Spacecraft bus miss-maneuver	< 0.001	96

The successful fly-by region is assumed to be Region I, shown in Fig. 1, which is a plot of the asymptotic aiming zones to avoid Sun, Canopus, or Earth eclipse by Mars for arrival between July 4 and July 18, 1965. If the fly-by trajectory asymptote lies within one of the eclipse zones, an eclipse will occur sometime during the fly-by mission phase. It is estimated that no look-angle restriction of the planetary instruments will be experienced for flights within

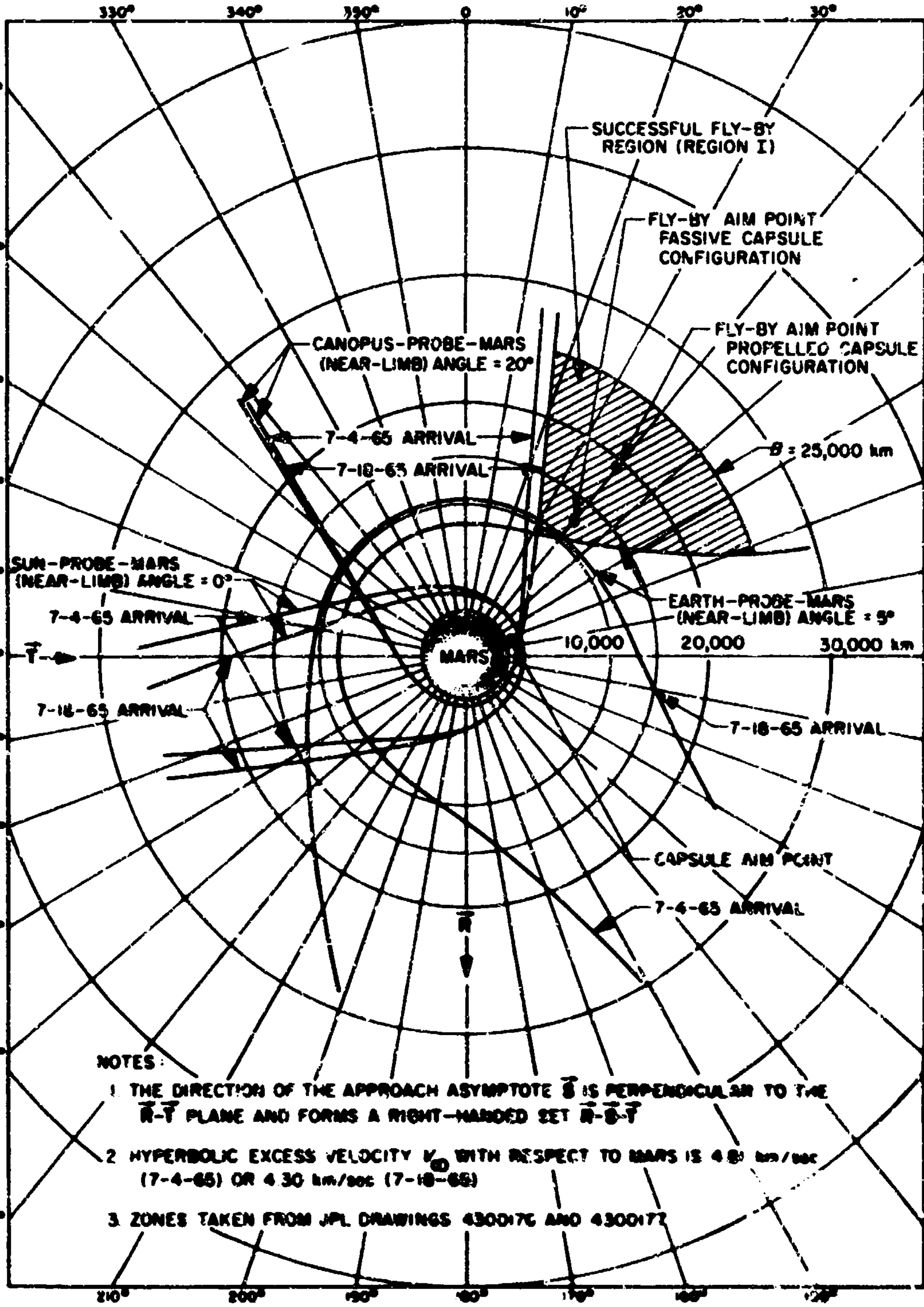

Fig. 1. Asymptotic aiming zones to avoid eclipse by Mars for arrivals between July 4 and July 18, 1965

Region I. The effect of the Sun eclipse would be to lose attitude control and solar-panel power. If the Canopus-probe-Mars near-limb angle is less then 20°, the star-seeker may be confused by Mars, in which case roll control will be lost. An Earth eclipse (Earth-probe-Mars near-limb angle $< 5°$) would lose telemetry during the eclipse period, but may not cause loss of data since the recorded data could be transmitted after the eclipse period. The outer boundary of Region I was assumed at 25,000 km radius B[1] from Mars. This results in a maximum periapsis of about 23,150 km (for $V_\infty = 4.8$ km/sec). This boundary will depend upon instrument resolution limits. Even though an Earth eclipse or a fly-by boundary of greater than 25,000 km could be tolerated, for the purpose of this investigation, the successful fly-by region is considered to be Region I (Fig. 1). The probabilities of being within Region I and the probabilities of impacting the planet (Table 1) were computed using a dispersion at Mars resulting from midcourse and approach correction errors shown in Table 2.

B. Propelled Capsule System

Many variations of the propelled capsule system are possible. They all have in common two basic advantages: (1) reduction in total propulsion system mass due to less propellant requirement to perform the deflection maneuver (capsule is far lighter than the bus), and (2) extremely reduced probability of the bus impacting the planet, since the spacecraft is always aimed on a fly-by trajectory.

[1] The impact parameter B is the distance from the center of Mars to the trajectory asymptote.

Table 2. Trajectory dispersions at Mars resulting from guidance errors

Guidance errors	km (1σ)
Instrument errors (JPL current estimate)	1,200
Radio-tracking error	2,000
AU error	assumed negligible
RMS total	2,340
Dispersion at Mars	**km (1σ)**
Dispersion resulting from an approach correction made 1,500,000 km from Mars	865
Dispersion resulting from an approach correction made 400,000 km from Mars	320

For the purposes of this investigation, the selection of the propelled capsule system was based upon the following requisites:

1. The capsule propulsion system should not require commands from the spacecraft bus, except for launch signal (the capsule rocket-motor impulse should be preset).
2. The system should be as simple as possible, with risk to the fly-by mission kept to a minimum.
3. The capsule should not employ an active guidance system.

To fulfill these desired requisites, the following systems seem most promising.

1. Propelled Capsule System with a Highly Corrected Fly-By Trajectory

This system uses essentially the same approach-phase sequence as the passive capsule system, except that the approach trajectory is the same as the fly-by trajectory, and the deflection maneuver is made with the capsule rather than the bus. For the approach sequence, two corrections are made as the spacecraft approaches Mars on a fly-by trajectory. Just after the completion of the second approach correction, the capsule is aimed by turning the spacecraft, then separated, and the capsule deflection maneuver impulse is provided by a fixed impulse solid-rocket motor.

This system has the two main advantages and meets the desired requisites listed in the foregoing, and provides a fly-by trajectory with the same dispersion of about ±800 km (2.5 σ) as for the passive capsule configuration. However, the fly-by mission can tolerate a dispersion considerably greater than ±800 km (2.5 σ). The following system takes advantage of this aspect.

2. Propelled Capsule System with a Simplified Approach-Phase Sequence

If a propulsion system is used to propel the capsule, the fly-by trajectory does not require the same degree of correction as the capsule trajectory. Since each maneuver presents some additional risks to the fly-by mission, reducing the number of correction maneuvers will improve the over-all probability of success. However, this improvement in reliability will come at the expense of accepting a larger dispersion in the periapsis of the fly-by trajectory. The most advantageous system from this point of view is briefly described as follows:

The midcourse correction will aim the spacecraft at a fly-by aim point in the center of Region I (as previously described in Fig. 1). The approach guidance measurements will be made as the spacecraft approaches the planet. The first set of measurements will be completed when the spacecraft is at a distance of about 1,500,000 km from Mars. If the trajectory is found to be within Region I, no approach correction will be necessary; but if the trajectory is outside Region I, an approach correction will be made and the spacecraft will be aimed on the fly-by trajectory. Assumed dispersions at Mars resulting from midcourse correction errors were taken from Ref. 3. The current JPL estimate of instrument errors is approximately 1,200 km (1 σ). The radio-tracking errors, 2,000 km (1 σ), and a negligible AU error result in an RMS total of approximately 2,340 km (1 σ). This 2,340 km is the semimajor axis of the 1 σ error ellipse; however, in this Report, the dispersion ellipse was conservatively assumed to be a circle of 2,340-km (1 σ) radius. By using this error circle, the probabilities of the fly-by trajectory being within Region I (not requiring an approach correction) and of impacting the planet are shown in Table 3.

The second set of approach guidance measurements will be completed when the spacecraft is approximately 400,000 km from Mars. From these and previous measurements, the fly-by trajectory will be determined and the required capsule deflection maneuver will be calculated. The capsule solid-rocket motor, with a fixed impulse, will be designed to perform the capsule deflection maneuver at a distance of 400,000 km from Mars, when the fly-by trajectory is at the outer extremity of Region I (B = 25,000 km). If the fly-by trajectory has B less than 25,000 km, the distance from the planet where the

Table 3. Approach trajectory dispersions for propelled capsule configuration

Degree of trajectory correction (last correction which was successfully completed)	Probability of trajectory being successful (within Region I, Fig. 1) percent	Probability of trajectory impacting planet (periapsis < 3 600 km) percent
Midcourse	77	1.6*
Midcourse plus approach correction	97	0.1

*This probability can be substantially reduced by biasing the midcourse correction aim point (see Ref. 6).

deflection maneuver is made will be adjusted so that the fixed impulse will direct the capsule towards the capsule aim point. From the spacecraft bus and capsule trajectory studies of Ref. 3, it was shown that a spacecraft-capsule eclipse by Mars will not occur even for the worst case (52° entry angle), if the fly-by trajectory has a radius B greater than 17,200 km. In this region the deflection maneuver will be made perpendicular to the approach-velocity vector. For trajectories with B less than 17,200 km, the deflection maneuver can be made at an angle ϕ less than 90° to the velocity vector. This will eliminate the spacecraft-capsule eclipse for most combinations of B and entry angle. The angle ϕ is limited to a minimum of about 60 to 70° in order that the dispersion in capsule entry angle does not become excessive. For fly-by trajectories on the boundary of Region I nearest the planet and an angle ϕ of 70°, an eclipse of up to 3-1/2 hours will occur, depending upon the capsule entry angle.

III. PROPELLED CAPSULE FEASIBILITY STUDY

A. Capsule Dispersion Analysis

The attainment of capsule dispersions within the allowable limits is of great significance in establishing the feasibility of using a propelled capsule. Based on the requisite that an active guidance system should not be used on the capsule, one approach to properly direct the rocket motor during firing is by means of spin stabilization. Another approach is the use of an attitude-stabilized capsule, which is currently under investigation at the Laboratory.

The general problem of propulsion of a spinning body has been analyzed in Ref. 4. The results show a dispersion angle (angle between actual impulse vector and aiming vector) and coning angle (average angle between thrust vector and capsule spin axis) as a function of initial attitude rate, side-thrust component and pitching moment due to misalignment, spin speed, burning time, and body moment of inertia. Reference 4 also provides attitude angles as a function of time and pitching moment for various spin speeds and ratios of moments of inertia.

The following assumptions were made for all cases:

Thrust vector to c.g. misalignment	= 0.01 rad (2.5 σ)
Thrust offset	= 0.050 in. (2.5 σ)
Initial attitude rate	= 0.050 rad/sec (2.5 σ)

The estimated capsule dispersions for the launching and execution of the capsule deflection maneuver are shown in Table 4. The contributing errors are

Table 4. Mariner B capsule launch and maneuver errors

Angular orientation errors (2.5σ)	Degrees
Basic spacecraft aiming error	1.5
Spacecraft aiming error due to capsule spin-up on spacecraft	2.5
Angular dispersions (δ) of capsule due to launching (Fig. 2), assuming a spin rate of 10 rad/sec	1
RMS total	~3
Deflection-impulse magnitude errors (2.5σ)	**Percent**
Total impulse variations due to propellant batch-to-batch variations	0.3
Total impulse variations due to an assumed propellant-temperature uncertainty (±60°F)	0.6
Total impulse variations due to loading errors	0.1
Coning error, assuming a spin rate of 10 rad/sec	0.25
RMS total	0.7

of two types: (1) those corresponding to a dispersion in the angular orientation of the impulse vector, and (2) an error in the effective magnitude of the impulse.

These capsule launch and maneuver errors are quite conservative. For comparative purposes, the dispersions computed on the Ranger capsule by Aeronutronics[2] are listed in Table 5.

[2]Aeronutronics, a Division of Ford Motor Company, Newport Beach, Calif.

Table 5. Ranger capsule launch and maneuver errors

Total angular orientation error	1.2° (2.5 σ)
Total impulse magnitude error	0.56% (2.5 σ)

Capsule dispersion estimates based on the data of Table 4 are listed in Table 6 for fly-by trajectories at the boundary of Region I which is nearest to the planet (B = 12,300 km) and farthest from the planet (B = 25,000 km). The dispersions are presented as in-plane dispersions (dispersions in the plane which contains the approach-velocity vector and the deflection-impulse vector) and out-of-plane dispersions (dispersions in a plane perpendicular to the approach-velocity vector). In-plane dispersions are of main concern since they are in the radial direction and seriously affect the capsule entry angle.

The out-of-plane dispersions are in the circumferential direction and are of much less concern because they have little effect on the entry angle. The approach guidance system accuracy was assumed to be the same for both the propelled and passive capsule configurations.

The results of this analysis demonstrate that, even though the errors assumed are quite conservative, the propelled capsule has the same entry-angle accuracy as the passive capsule. The only exceptions are for fly-by trajectories near the top boundaries of Region I. For trajectories near this corner the capsule entry angle will vary from about 0 to 57° for the 2.5 σ dispersion ellipse if the capsule aim point is at 20° N latitude[3], as shown in Fig. 2. The 2.5 σ

[3]Latitude as used here is the angular distance above the $\overline{S}\,\overline{T}$ plane.

Table 6. Capsule dispersions (2.5σ) for propelled capsule

Capsule dispersion (2.5σ) at Mars due to error source listed

Fly-by trajectory position	Region 1, Fig. 1 Nearest to planet (B = 12,300 km)		Region 2, Fig. 1 Farthest from planet (B = 25,000 km)	
Distance from Mars at capsule separation	180,000 km		400,000 km	
Angle ϕ between approach-velocity vector and deflection-impulse vector	70°		90°	
Dispersion plane	In-plane (radial)	Out-of-plane (circumferential)	In-plane (radial)	Out-of-plane (circumferential)
Error Source				
Approach guidance position determination error	±700 km	±700 km	±800 km	± 800 km
Angular error in velocity impulse, ±3° (2.5σ)	±205 km	±500 km	± 28 km	±1100 km
Impulse magnitude error, 0.68% (2.5σ)	± 60 km	0	±150 km	0
Ignition-time error for capsule rocket-motor ignition, 10 sec (2.5σ)	2.4 km	0	2.5 km	0
RMS total (2.5σ)	±730 km	±860 km	±812 km	±1360 km

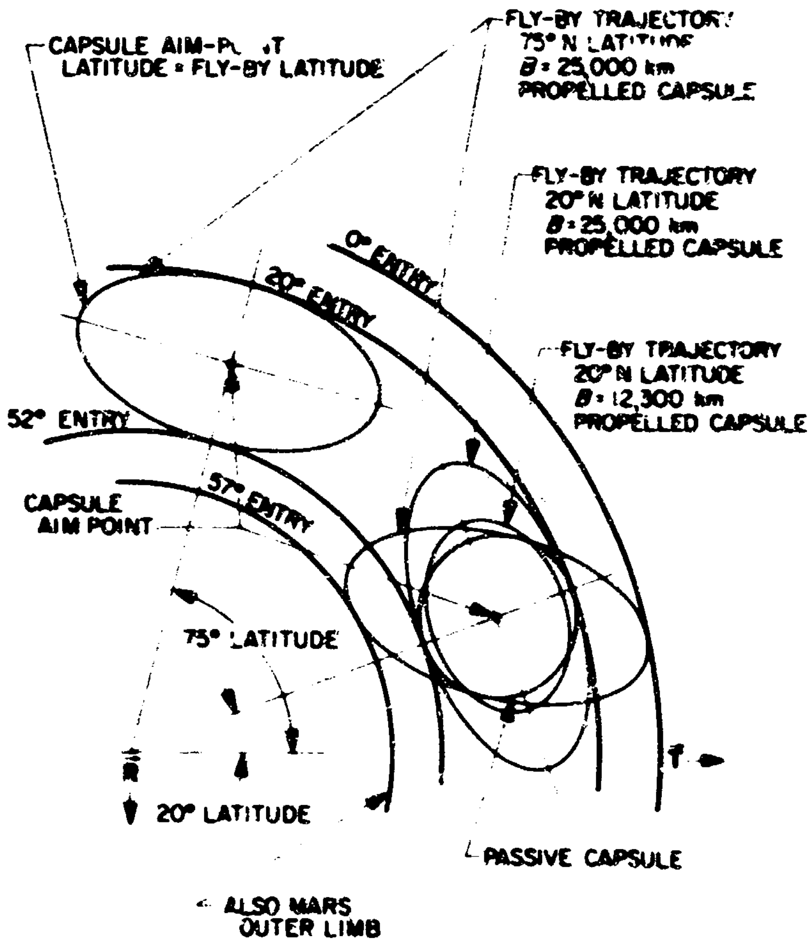

Fig. 2. Capsule dispersions (2.5 σ) for propelled and passive capsule configurations (V_{∞} = 4.5 km/sec)

dispersion ellipse will always be within the 20 to 52° entry-angle corridor if the capsule aim point is established at the same latitude as the fly-by trajectory. Figure 2 shows the dispersion ellipses for B = 25,000 km and for equal capsule and fly-by latitude of 20° (minimum within successful fly-by region) and 75° (maximum within successful fly-by region).

B. Capsule-Bus Interactions

The next problem investigated was the interaction of the capsule and bus during separation. It was decided to assume that whether or not a spinning capsule would be released, the method of ejection would be the same. The only difference, then, is the effect of spin-up. It was also decided that any spin-up mechanism should be on board the capsule. Figure 3 represents two typical ways of satisfying this constraint. As shown, an electric motor could be used to spin up the capsule while it is attached to the bus. It is estimated that, by using the roll jets to provide the reaction torque during spin-up, a long spin-up period (10 to 20 minutes) would be required. During this time the spacecraft would be oriented off the Sun, and the pitch and yaw jets would either be cut out to prevent gyroscopic cross-coupling or the control torques resolved. The spacecraft aiming error of 2.5° (2.5 σ) due to the capsule spin-up on the spacecraft, used in the dispersion analysis (see Table 1), assumes this type of spin-up. Another possible method of spin-up while attached to the bus is to counterbalance the torque required for capsule spin-up by spinning up a flywheel. Such an arrangement will allow faster spin-up and will not require the near-continuous use of roll jets to provide the reaction torque during spin-up.

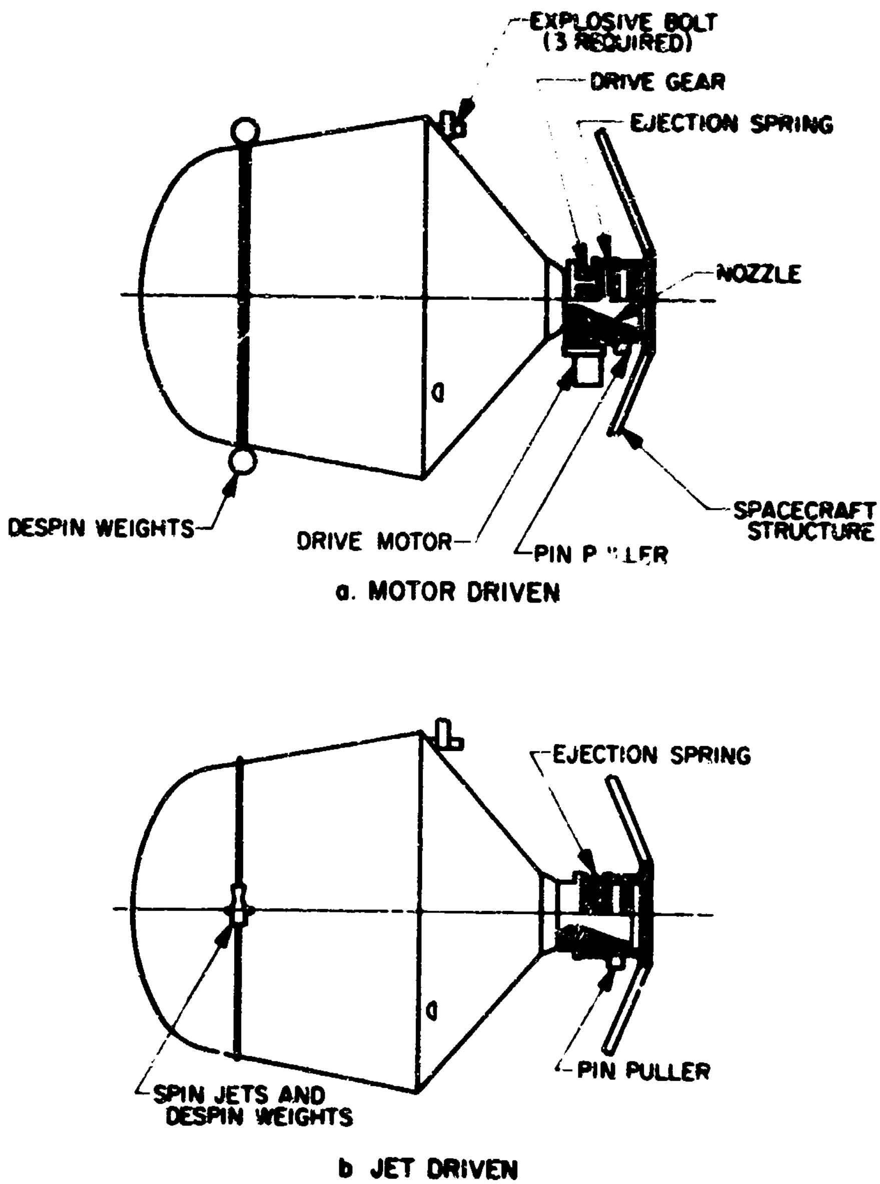

Fig. 3. Typical spin-up methods

An alternate technique of reducing spacecraft torque and allowing a rapid spin-up is by the use of spin jets. However, the bearing friction and jet-gas impingement would be felt by the bus. It is believed that with proper design these effects can be made small. In order to completely eliminate these interactions, the possibility of spinning up after separation was investigated. Reference 4 provided attitude rate, spin-jet malalignments, thrust differences, and unbalance. The calculation of attitude angle and attitude rate vs time was based on the following assumptions:

Spin-jet thrust-difference malalignment with tangent plane	=	±0.01 rad
Malalignment with spin-jet plane	=	±0.01 rad
Differential radius	=	0.010 in.
Displacement from spin-jet plane	=	±0.010 in.
Nominal distance from c.g. to spin-jet plane	=	0

It can be shown that for a given launcher length the attitude (pitching) rate at separation of a nonspinning vehicle will vary directly as the launching velocity (assuming the torque at ejection is proportional to the work required of the launching mechanism). Assuming a 1-ft/sec launch velocity, the tumbling rate was estimated to be 3°/sec. With this tumbling rate it is apparent that spin-up must occur very close to the bus so that the pitch angle does not become excessive. As a matter of fact, it must be within less than 1 ft to stay within allowable limits. Therefore, there appears to be very little advantage in separation prior to spin-up.

So long as ignition of the capsule rocket motor occurs at a sufficient distance from the bus, it would appear that launching the capsule by spinning up while attached to the bus is quite feasible. In Ref. 5 it was estimated that the separation distance should be about 275 ft at ignition based upon a capsule initial acceleration of 0.1 g. The maximum distance which would be required to accommodate any capsule acceleration is estimated to be 385 ft. Thus, with a capsule ejection velocity of 1 ft/sec, a coast period of about 6 minutes would be required. The ignition and despin signals could be given by a timer which is started at capsule launch. Despin could be accomplished by a "yo-yo" device or by solid-propellant despin motors.

The results of these analyses and investigations indicate that a propelled capsule system is quite feasible and that launching can be accomplished by spinning up the capsule while attached to the spacecraft.

IV. ADVANTAGES OF A PROPELLED CAPSULE

With the feasibility established, the next task was to examine more closely the apparent advantages of using a propelled capsule.

A. Mission Reliability

A reliability analysis was performed for both the passive and propelled capsule configurations. The purpose of this analysis was to estimate the probabilities of success for the fly-by and capsule phases of the mission. Table 7 shows the spacecraft system reliability estimates made by personnel of Divisions 34, 35 and 38. In this Report, spacecraft bus and capsule are broken down into

Table 7. Reliability estimates for spacecraft systems[a]

System	Guidance observations, telemetering, and computation systems		Command and sequencing system		Attitude-control and commanded-turn system		Spacecraft-bus propulsion system		Spacecraft autopilot		Capsule launching system, including separation from spacecraft and capsule spin-up (if required)		Capsule propulsion system		Capsule timer for ignition and despin signals		Capsule despin system	
Source (responsible Division)	34		34		34		38		34		35		38		34		35	
Failure mode[b]	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Maneuver																		
First approach correction	0.95	0.995	0.98	0.995	0.98	0.99	0.98	0.998	0.98	0.98	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Second approach correction	0.98	0.995	0.99	0.995	0.99	0.995	0.99	0.998	0.99	0.99	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Capsule launch maneuver																		
Propelled capsule	0.95[c] to 0.99[d]	0.99[c] to 0.995[d]	0.98	0.99	0.98[e]	0.995	1.0	1.0	1.0	1.0	0.85[f]	0.90[f]	1.0	1.0	1.0	1.0	1.0	1.0
Nonpropelled capsule	1.0	1.0	0.995	0.999	1.0	1.0	1.0	1.0	1.0	1.0	0.996	0.999	-	-	-	-	-	-
Capsule propulsion maneuver	1.0	1.0	0.98	0.995	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.99	1.0	0.99	1.0	0.90	1.0
Spacecraft-bus miss-maneuver	0.95[c] to 0.98[d]	0.995	0.98[c] to 0.99[d]	0.995	0.98[c] to 0.99[d]	0.99[c] to 0.995[d]	0.98[c] to 0.99[d]	0.998	0.98[c] to 0.99[d]	0.98[c] to 0.99[d]	1.0	1.0	-	-	-	-	-	-

[a]These reliability estimates assume that prior functions of the system have been successful.

[b]Failure modes: 1. System fails and is unable to function but does not abort spacecraft bus. (System failures which may cause the flyby to be outside the successful area are also considered to be mode 1.)
2. System fails and aborts the spacecraft bus.

[c]System reliability with no prior approach correction.

[d]System reliability with prior approach correction.

[e]Possible attitude error due to capsule spin-up.

[f]These numbers are revised reliability estimates (after the presentation to R. Parks on October 4, 1961). The original estimates were 0.935 and 0.991.

systems as shown in Table 7. The systems which are not listed are assumed to have no bearing on this study. For systems which affect the fly-by mission, reliability estimates are given for the following two failure modes:

1. System fails and is unable to perform the maneuver but does not abort spacecraft bus.
2. System fails and aborts spacecraft bus.

The approach phase of the mission is divided into five maneuvers for comparison purposes. Maneuvers not listed are not affected by the alternatives under study. Reliability estimates assume that prior functions of the system (if required) have been successful.

Table 8 shows the effective system reliabilities. These are the probabilities that a system will not cause a mission failure. The effective and actual reliabilities are the same for mode 2 system failures (system fails and aborts spacecraft bus). For mode 1 system failures (system fails or is unable to operate but does not abort spacecraft bus), the effective system reliability is based on the actual system reliability and probability that a system failure will cause mission failure. For example, at the time of the first approach correction for the propelled capsule configuration, if the spacecraft-bus propulsion system has a mode 1 failure and thus is unable to make the first approach correction, the fly-by mission still has a probability of success of 77%, because this is the probability that the bus propulsion system will not be required to operate (see Table 3). The effective reliability of the spacecraft-bus propulsion system is given by

$$R_{eff} = R_{act} + (1 - R_{act}) P$$

where

R_{eff} = effective bus propulsion system reliability

R_{act} = actual bus propulsion system reliability

P = probability that a maneuver failure will not cause mission failure

For this example:

$$R_{act} = 0.98$$

$$P = 0.77$$

$$R_{eff} = 0.98 + (1 - 0.98)(0.77)$$

$$R_{eff} = 0.9954$$

Using the effective system reliabilities listed in Table 8, the probabilities of mission success were computed as shown in Table 9.

For comparison, the ratio of probabilities for the passive and propelled-capsule configurations are presented in Table 10.

Table 10 indicates that the fly-by mission has approximately 12% higher probability of success with the propelled capsule configuration than with the passive capsule configuration. However, the probability of capsule mission success is estimated to be 15% lower for the propelled capsule configuration.

Another way of comparing mission reliability is to consider the probabilities of failure. These are shown in Table 11. Thus, by employing a propelled capsule the probability of mission failure can be reduced by 36% for the fly-by mission and increased by 42% for the capsule mission.

Table 8. Effective spacecraft system reliabilities

Spacecraft system	Fly-by mission		Capsule mission	
	Propelled capsule configuration	Passive capsule configuration	Propelled capsule configuration	Passive capsule configuration
Guidance, observation, telemetering, and computation systems	0.978	0.916	0.938	0.916
Command and sequencing system	0.978	0.955	0.940	0.951
Attitude-control and commanded-turn systems	0.988	0.952	0.968	0.952
Spacecraft-bus propulsion system	0.995	0.963	0.994	0.963
Spacecraft bus autopilot	0.991	0.937	0.991	0.937
Capsule launching system including separation from spacecraft and capsule spin-up	0.90	0.999	0.85	0.995
Capsule propulsion system	1.0	- -	0.99	- -
Capsule timer for ignition and despin signals	1.0	- -	0.99	- -
Capsule despin system	1.0	- -	0.90	- -
Product of effective reliability	0.840	0.751	0.630	0.744

Table 9. Probabilities of mission success

Capsule configuration	Mission success probabilities (successful fly-by area Region I, Fig. 1)	
	Fly-by mission	Capsule mission
Propelled capsule	$0.84\ P_oR_b$	$0.63\ P_oR_bR_c$
Passive capsule	$0.75\ P_oR_b$	$0.74\ P_oR_bR_c$

P_o = Probability of success of fly-by and capsule mission through launch, midcourse, and coast

R_c = Effective reliability of capsule systems not affected by capsule propulsion

R_b = Effective reliability of spacecraft bus systems not affected by capsule propulsion

Table 10. Ratio of probabilities of mission success for passive and propelled capsule configurations

Fly-by mission*

$$P_1 = \frac{\text{Probability of success of fly-by mission with propelled capsule configuration}}{\text{Probability of success of fly-by mission with passive capsule configuration}} = \frac{0.84\ P_oR_b}{0.75\ P_oR_b} = 1.12$$

Capsule mission*

$$P_2 = \frac{\text{Probability of success of capsule mission with propelled capsule}}{\text{Probability of success of capsule mission with passive capsule}} = \frac{0.63\ P_oR_bR_c}{0.74\ P_oR_bR_c} = 0.85$$

*For notation of symbols, see Table 9.

Table 11. Ratio of probabilities of mission failure for the passive and propelled capsule configurations

Fly-by mission

$$F_1 = \frac{\text{Probability of failure with propelled capsule configuration}}{\text{Probability of failure with passive capsule configuration}} = \frac{1 - 0.84}{1 - 0.75} = 0.64$$

Capsule mission

$$F_2 = \frac{\text{Probability of failure with propelled capsule configuration}}{\text{Probability of failure with passive capsule configuration}} = \frac{1 - 0.63}{1 - 0.74} = 1.42$$

The reliability estimates presented in Table 7 indicate that for the propelled capsule configuration, the potential causes of failure are attributed to the capsule launching and despin systems. If a considerable amount of effort could be put into development of these systems, it might be possible to increase their reliabilities. The effect of these improved reliabilities upon the probabilities of mission success are shown in Table 12.

If these reliabilities can be achieved, then, using the propelled capsule configuration, the probability of success can be increased by 21% for the fly-by mission and by 5% for the capsule mission, as shown in Table 13.

B. Weight Reduction

Weight estimates for the propelled capsule configuration, utilizing spin stabilization, are shown in Table 14.

Table 12. Effect of improved launching system and despin system reliabilities upon probability of fly-by and capsule mission success with propelled capsule configuration

Assumed reliability improvements

System	Capsule launching system		Capsule despin system	
Failure mode	1	2	1	2
Improved reliability	0.95	0.98	0.95	-
Reliability estimate from Table 7	0.85	0.90	0.90	-

Probabilities of mission success

System reliabilities	Fly-by mission	Capsule mission
System reliabilities with improved reliabilities shown above	(0.91) $P_o R_b$	(0.78) $P_o R_b R_c$
System reliabilities from Table 7	(0.84) $P_o R_b$	(0.63) $P_o R_b R_c$

Table 13. Ratios of probabilities of mission success based upon improved launcher and despin system reliabilities

Fly-by mission

$$P_1^1 = \frac{\text{Probability of success of fly-by mission for propelled capsule configuration}}{\text{Probability of success of fly-by mission for nonpropelled capsule configuration}} = \frac{0.91\ P_o R_b}{0.75\ P_o R_b} = 1.21$$

Capsule mission

$$P_2^1 \quad \frac{\text{Probability of success of capsule mission for propelled capsule configuration}}{\text{Probability of success of capsule mission for nonpropelled capsule configuration}} = \frac{0.78\ P_o R_b R_c}{0.74\ P_o R_b R_c} = 1.05$$

Table 14. Weight estimates for propelled capsule configuration utilizing spin stabilization

Spacecraft weight	1370 lb
Capsule weight without propulsion system	230 lb
Deflection impulse	296 m/sec

System weights, lb		
Spin-up motors		
Deflection impulse motor		30.0
Propellant (I_{sp} vac. 285)	26.7	
Inert	3.3	
Spin-up motors (2)		3.5
Propellant	1.75	
Inert	1.75	
Sequence and power supply (approx.)		1.5
Attachments, structure, and despin system (approx.)		5.0
Launcher weight		15.0
Total		55.0
Electric motor		
Deflection impulse motor		30.0
Propellant (I_{sp} vac. 285)	26.7	
Inert	3.3	
Drive motor and gear box (spin-up)		2.5
Power supply for drive motor		2.0
Attachments and structure (approx.)		5.5
Launcher weight		15.0
Total		55.0

Table 15 shows a comparison of the weight of the passive capsule configuration (from Ref. 3), where the deflection maneuver is performed by the midcourse propulsion system, and the weight of the propelled capsule configuration (from Table 14).

Table 15. Weight comparison of passive and propelled capsule configurations

Configuration	Weight, lb	
Passive capsule		
Midcourse propulsion system mass required to perform the deflection maneuver and second approach correction	112.0	
Launcher mass for passive capsule	10.0	122.0
Propelled capsule		
Total mass of capsule propulsion system, launcher, sequencer, spin-up and despin systems	55.0	55.0
Net mass saving for the propelled capsule configuration utilizing spin stabilization		67.0

C. Possible Elimination of Spacecraft-Bus Sterilization

Based on system reliability estimates in Table 7, and the effect of a maneuver failure shown in Table 1 and Table 3, the probabilities of the spacecraft bus impacting Mars are lower for the propelled capsule configuration than for the passive capsule system, as shown in Table 16. In these estimates, it was assumed that the probability of the spacecraft bus impacting the planet in the event of a system failure would be the same as the probability of impact if the maneuver and subsequent maneuvers were not performed.

Table 16. Over-all probability of spacecraft bus impacting Mars (if spacecraft is successful through launch and midcourse correction)

Configuration	Perc[illegible]
Passive capsule	22
Propelled capsule	0.25

If the probabilities of launch and midcourse-maneuver success are included, the estimated total over-all probability of impacting Mars will probably be of the order of 0.1% to 0.2%. This probability is of the same order as the probability of the unsterilized Agena B booster impacting Venus during the Mariner R mission.

V. ELIMINATION OF SPACECRAFT-CAPSULE ECLIPSE BY MARS

The probability of a spacecraft-capsule eclipse occurring just after capsule descent is approximately 50% for the passive capsule configuration. If a propelled capsule is used the probability of eclipse can be reduced to about 5%. This improvement is attributed to the greater periapsis distance for most of the fly-by trajectories used with the propelled capsule configuration. For the non-propelled capsule configuration, the probability of eclipse could also be decreased to 5% by increasing the fly-by aim-point radius B to about 17,000 km; however, this increase in separation distance would require an additional 20 lb of propellant for the miss maneuver. Since it is expected that communication lock will be lost because of the rapid doppler shift during atmospheric entry as well as during spacecraft-capsule eclipse, reducing the probability of eclipse will not allow elimination of the reacquisition capability of the spacecraft receiver, although it will increase the time for data transmission and improve the probability of mission success.

VI. CONCLUSIONS

1. The results of the capsule dispersion analysis and the capsule-bus interactions study establish the feasibility of using a propelled capsule for the Mars split-capsule mission.
2. The results of the reliability analysis indicate that, if the prime mission is the fly-by, the propelled capsule configuration is the better choice, since it results in a 12% higher probability of fly-by mission success. However, if the capsule mission is the more important, the passive capsule configuration is the better choice since it results in a 15% higher probability of capsule mission success.
3. An approximate weight saving of 67 lb can be achieved by using the propelled capsule configuration as opposed to the passive capsule configuration.
4. The probability of the spacecraft impacting Mars can be reduced from about 22% to 0.25% by utilizing the propelled capsule configuration as compared to the passive capsule configuration.
5. For the propelled capsule system, the probability of spacecraft-capsule eclipse is approximately 5% as opposed to 50% for the passive capsule system.

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